

NUMERICAL ANALYSIS OF INDUCTANCE LOSS DUE TO INFLUENCE OF WINDING DESIGN

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ABSTRACT

There are two types of inductor winding, namely multiple layer winding and single layer winding. It is known that the performance of a multiple layer inductor degrades over time at high frequencies stresses and eventually becomes worse than that of a single layer design inductor. An alternative is to use thinner laminated conductors. However, these conductors are susceptible to inductance loss effects, which can lead to increased winding fault or poor performances of the EMI suppression inductor. In designing winding to EMI suppression inductor, the most importance aspect is to understand the winding failure reason and area due to the inductance loss effects. This paper is to investigate the factors influencing inductance losses, the shape of winding strategies of faulty failure zone, simulation trials with proposed solution candidates. This study is limiting to copper winding conductor for EMI suppression inductor, a popular ferrite material family.

KEYWORDS: EMI Suppression Inductor, Inductance Loss, Winding Design

INTRODUCTION

As some EMI suppression inductors are designed to carry relatively large amounts of current [1], considerable power can be dissipated in the inductor even though the amount of resistance in the inductor is small. This power loss is called copper or inductance loss. The copper loss of the EMI suppression inductor can be calculated by multiplying the square of the current in the inductor by the resistance of the winding. However, in some applications, because of component size requirements, the use of inductors with multiple windings is unavoidable. While winding optimization plays a significant role in improving thermal performance, most of the work has focused on inductors with single layer winding [4] [5]. In EMI inductors family with ferrite magnetic material, the ferrite core and the gap between conductors strongly affect the conductor diffusion affect. To simplify, the problem it is at first assumed, that the insulation thickness is infinitely small. These spiral wound windings do not conduct during this period, but the result is an effect that contributes to the inductance loss. An inductor with a single layer winding generally has lower high frequency losses at most operating temperatures because of lower stresses as compared to an inductor with multiple layers.

EMI Inductor Winding Design Parameter

The parameters and its influence on the winding design of an inductor were investigated, using Taguchi's method, with the aim of selecting an optimum set of parameters. An experimental design was use to determine the optimal combination of parameters corresponding to various design designs that would result in minimum fall out ratio and minimum machine error processing [2]. Based on the results from the analysis, it is concluded that the winding width is the most significant parameter related to fall out ratio or inductor faulty. Inductance faulty will lead to inductance loss. Every

winding inductor magnetism phenomenon can be characterized by a partial differential equation system, which is also known as Maxwell's equation [9] and [6]. Changing winding design of the EMI suppression inductor type, we must first consider its electrometric behavior. The equation system defines the relationship between electromagnetic field quantities such as electric field intensity, \vec{E} , magnetic field intensity, \vec{H} , electric flux density, \vec{D} , magnetic flux density, \vec{B} , and the source densities, such as electric current density, \vec{J} , and the electric charge density, ρ . The numerical analysis of an arrangement which requires field calculations can be executed according to the Maxwell's equations which are given as follows [3].

$$\oint_{\Gamma} \vec{D} \cdot d\vec{\Gamma} = \oint_{\Omega} \rho d\Gamma \quad (1)$$

The above equations are also known as the integral form of Maxwell's equations as expression and in classical form. For the development of the potential formulations of field problems, it is easier to use the differential form of this collection of equations. This equation represents that the current density, \vec{J} , which means the current flowing in the coils, the summation of the source current density, the eddy current inside a conducting material and the displacement currents, produced by a time varying electric field, generate a magnetic field intensity, \vec{H} . The classical form of it says that to the summation of currents, which are determined by the surface integral of current densities flowing across the area Γ . This equation describes that the time varying magnetic field actually generates the electric field. In time dependent cases, the electric and the magnetic field submit that the first and second Maxwell's equations are coupled. Therefore, the time variation when its expose to inductance loss inner system the magnetic field influences the electric field with reverse orientation in the studied region, and then the produced electric field generates eddy current inside the conducting material, which modifies the source magnetic field. The Equation 1 can be approximated as current densities flowing across the inductor winding area of the EMI inductor experiment model. The constraints of the optimization are subtly different from wound winding, foil winding or litz wire winding. In this study, the multiple layer winding method has been selected among the three methods mentioned as follows for the EMI inductor. Assuming single layer $F_r=1$, with six turn 6, $n = 6$ with the number of layers equal to the number of turns, $F_r = n$. In order to ensure equal current in each conductor segment, this strategy can only be used to obtain a number of layer smaller than the number of turns, such that the conductors in different layers are connected in series. If the layers are in parallel, the current will not be equal and the analysis does not apply, unless other measures are taken to ensure similarity in the layers. For EMI inductors, multiple small gaps can be used to estimate a distributed gap. Since there are many accurate and sophisticated models exist [12], out of which a model of inductance lost in a wire winding has been selected in order to facilitate an optimization that more clearly shows the effect of conductor resistivity on the final performance. Since there is no other layer inducing fields, the inductance loss depends only on the resistance stress of the layer where current flows and is proportionate to the square root of frequency. For multiple winding with a large number of layers, a wire diameter that is not too large as compared to copper depthless and a one-dimensional field configuration, the conductor resistance factor can be approximated by [10]:

$$F_r = 1 + \frac{\pi^3 \omega^2 \mu_0^2 n^2 d^4}{1.789 p^2 b_w^2} \quad (2)$$

where π is the number of strands in parallel, d is the diameter of conductor, p is the self resistivity, b_w is the breadth of the winding window, μ_0 is the permeability of free space and ω is the radian frequency of a sinusoidal

waveform frequency [10]. The optimum wire diameter can be found by setting the derivative of power loss with respect to d equal to zero. This result is an optimum conductor resistance factor $F_r = 1.5$ [8] will be used in the modeling. In a multiple winding design, the inductor core thickness that minimizes the resistance is the one which gives a resistance factor equal to 4/3 [10], based on similar approximations to those used for multiple layer windings. Operating at high frequency may require thicker conductor layers or bigger conductor diameter wire than is practical. Secondly, the additional effort required for a multiple winding design may be impractical in comparison to achievable decrease in loss, particularly if a large number of layers are required. Thirdly, the current waveform may not be a single frequency. And finally the current waveform may contain many components in a single application system; even if the design is optimized for low frequency, the losses may be larger. Also, the field is one-dimensional and the Dowell model is an exact solution of Maxwell's equations. The conductor resistance factor $F_r = \frac{R_{ac}}{R_{dc}}$ can be expressed as [9] in Equation 3.

$$F_r = \Delta \left[\frac{\sinh 2\Delta + \sin 2\Delta}{\cosh 2\Delta - \cos 2\Delta} + \frac{2(p^2 - 1)}{3} \frac{\sinh \Delta - \sin \Delta}{\cosh \Delta + \cos \Delta} \right] \quad (3)$$

Where Δ is the ratio of layers' thickness to copper thickness and, μ the conductor permeability and f is the frequency of a sinusoidal current. Above conductor resistivity factor model is accepted and used for many multiple design [12]. Once a particular strategy is selected, other modeling can be used to predict the performance more precisely. For smaller values, $\Delta = 1$ are typically advantageous in a multiple winding, consequently, the Equation 5 can be approximated as [11]:

$$F_r = \left[1 + \left(\frac{5p^2 - 1}{45} \right) \Delta \frac{4}{ml} \right] \quad (4)$$

Where $\Delta \frac{4}{ml}$ is the value of area for multiple winding. For smaller values of Δ , it is possible to calculate the loss based on the assumption that the current flows in a layer thickness to copper thickness.

Winding Design Influence

The change in the inductor's design assuming the number of winding turns remain unchanged, will not change the EMI inductor characteristics drastically. This is owing to the current entering and leaving the terminal of circuit elements is identical, which is based on lumped element circuit theory whereby the current distribution is considered uniform when there are no changes in the inductor physical design, in a phenomenon known as wave interference [7]. Inductance loss model developed to determine winding losses, assuming constant resistance with no leakage. The model winding loss is defined in Equation 5:

$$\mu_L = \frac{B}{H} \quad (5)$$

Where μ_L is permeability ratio of the magnetic flux density, B to magnetic field density, H . The overall permeability of a winding can be obtained from numerical simulations [36]. The initial permeability, μ_i and the permeability of air gap is assumed as 0.15 and $4\pi \times 10^{-7}$ H/m (ideal case) respectively. The initial permeability is measured

on a pot-core inductor using toroidal cores at very low applied field with a flux density of less than 0.1mT. Initial permeability is a function of the measured value of inductance, L the calculated value of inductor factor, C and μ_0 , N and B_L , as given by Equation 6.

$$\mu_i = \frac{L \cdot C}{\mu_0 N^2 B_L} F_r \quad (6)$$

Table 1 shows inductance reference values of a semi inductor and their corresponding self-inductance values, B_L .

Table 1: EMI Inductor Characteristic of Self-Inductance Value

Item Type	Emi Inductance	B_L (10 μ)
1	1.4 μ H	0.029
2	2.3 μ H	0.028
3	2.9 μ H	0.027

The inductor self-inductance value, B_L of a 1 (one) wire-wound turn, is customizable and specific for a given inductor. N refers to the number of turns of an inductor. The F_r self-resistances are often referred to as series resistance since the conductor is wound around multiple times to create a multi-series magnetic resistance field as discussed in pervious section. A higher ratio indicates lower winding inductance-loss, with the ideal condition being no losses [2]. But, this condition is very difficult to achieve as the design of the inductor has to be an ideal one. Inductance reactance can be calculated [6] for coils of any design that can be decomposed into the coaxial circular ring. In general, Equation 7 can be used to calculate the potential inductance loss of different winding designs. The inductance calculation [1] is defined in terms of the number of turns required in Equation 7 below. Where L is equivalent to inductance, A_L is equivalent to an inductor factor of the area and X is equivalent to the number of turns.

$$L = A_L X^2 \quad (7)$$

In order to illustrate the different modeling approaches to predict winding fault, Figure 2 and Figure 3 EMI inductor cross section of the modeled design for round and cone winding. The winding intersection strategy has a great influence on copper effect. Therefore, it is quite interesting to compare the value where all designs have purposely been simulated with high frequency and temperature until it fails. Table 2 presents the value of the faulty inductances by actual measurement in laboratory, at which intersection is turning into two (2) different designs. The cross section validation modeling of different shape has been compared with actual fault measurement and calculated using Equation 7 above to predict inductance loss.

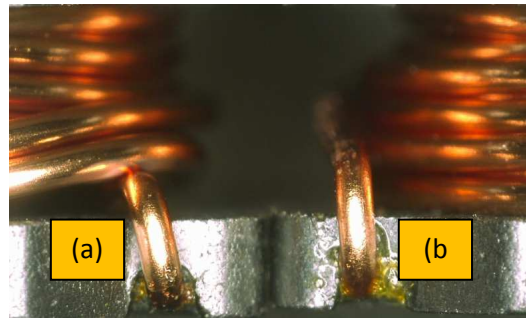


Figure 2: Winding Design Fault Zone (a) Cone (b) Round

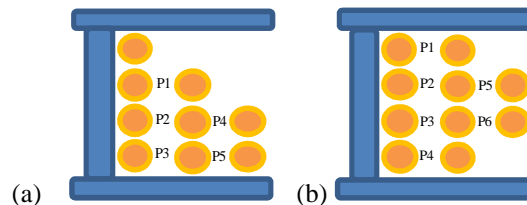


Figure 3: Winding Design Fault Zone (a) Cone (b) Round

Table 2: Cross Section Fault Validation Measurement in Laboratory Condition

Emi Inductor	Inductance Loss (Henry)
Round Winding	2.32
Cone Winding	1.85
Winding Loss %	25.4

The EMI inductor is assumed to be composed of a maximum of three layers of intersecting winding in parallel, illustrated by P1 to P8 as the number of turns. The results in Table 2 demonstrate the Round EMI inductor fault at the intersection turning P4 and Cone EMI inductor failure occurred at winding number P3. These two designs were validated by the measurement of faulty inductors in laboratory. The rest P later that not found fault zone indicates no inductance loss exist between intersection conductors of best winding layer of that particular design. Un-optimized EMI winding design could render high winding stresses. Cone EMI suppression inductor are comparatively better than round EMI suppression inductor winding inductors with improved 25% of inductance loss. Winding fault and inductance loss can be reduced when optimized shape is chosen. Besides, wire wound during the conductor wound-turning prevents failures as it decreases field deterioration and winding. Though a numerical model has been previously developed [3] to determine an optimal pattern for gapped space inductors based on a fixed strand diameter with resistance.

CONCLUSIONS

An analytical method to improve the inductance losses of the EMI suppression inductor design of a designated size, with a defined gap between conductor layer and has been analysis. The numerical solution makes it simpler to calculate inductance loss and predict winding fault zone of the EMI inductor, by observing models of different design with a given set of parameters. This is an essential step towards optimizing multiple winding for all type of inductors in the industry. The contributions of this paper are new insights and understanding of EMI suppression inductor type for different winding design and new inductance loss model has been developed. An optimal model for selection of winding type is optimized.

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